Full Length Research

SYNERGISTIC EFFECTS OF EARTHWORMS AND SOIL MICROORGANISMS ON LITTER DECOMPOSITION IN SUDANO-GUINEA SAVANNAH ZONE OF NGAOUNDERE, CAMEROON

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The impact of interaction of functional groups of soil organisms on litter decomposition in the tropical savannahs is poorly investigated. Microcosm experiments on synergistic effects of earthworms and soil microorganisms on litter decomposition was conducted in laboratory in the constant conditions of temperature and humidity on leaf litters of six contrasting plant species of sudano-guinea savannahs of Ngaoundere, Cameroon. These are *Anacardium occidentale* L., *Annona senegalensis* Pes., *Combretum molle* R. Br. Ex G. Dom., *Syzygium guineense* var. *guineense* (Willd) D.C., *Syzygium guineense* var. *macrocarpum* (Engl.) F. White and *Ximenia americana* L. Samples of each plant species have been incubated in microcosms on four types of soil: 1) sieved soil without earthworms (NS), 2) sieved soil with earthworms (NE), 3) sieved and sterilized soil without earthworms (SS) and 4) sieved and sterilized soil with earthworms (SE). For each treatment, 60 samples of 7±0.01g of each litter types were weighed and placed on the top soil of microcosms. Three samples of each plant species at each treatment were removed at 15, 30, 50, 70 and 120 days. Their dry mass remaining and decay rate were determined. Results showed that during 120 days of incubation, dry mass remaining varied from 4.96% in *X. americana* for the treatment with sieved soil containing earthworms (NE) to 87.21% in *S. guineense* var. *macrocarpum* for treatment with sterilized soil without earthworms (SS). Litter decomposition rate was significantly and negatively correlated with polyphenol compounds at all treatments. Inversely no correlation was found with lignin. Relative synergistic effects of earthworms and microorganisms to litter decomposition ranged from 12.73% in *S. guineense.* var. *guineense* to 44.75% in *X. americana* according to plant species and were controlled by physico-chemical characteristic of litter. In short, interaction of earthworms and microorganisms provided a significant contribution to litter decomposition in the Ngaoundere savannahs. These results showed the importance of preserving all soil fauna diversity in this region for assuring efficiently nutrient cycling and contributing to soil fertility management.

Keywords: Earthworms, Litter decomposition, Synergistic effect, Microorganisms, Sudano-guinea savannah, Ngaoundere, Cameroon.

INTRODUCTION

Litter decomposition process represents an essential phase of the organic matter and nutrient cycle (Leon and Nelson, 2014). Litter decay rate is a factor that largely determines forest soil fertility and its regulation plays an important role in ecosystem functioning (Swift et al., 1979) as primary production and nutrient cycling (Cardinale et al., 2006; Elser et al., 2007). Most of the plant litter from above ground plant production is supplied in the form of leaves, which decompose much faster than the woody litter components produced both above- and below-ground in ecosystems. Numerous factors, including resource quality (Maisto et al., 2011; Parsons et al., 2014), climate (Kurzatkowski et al., 2004; Dhanya et al., 2013; Suseela et al., 2013; Bothwell et al., 2014) and soil nutrient availability (McClaugherty et al., 1985; Li et al., 2011) for plant growth and forest disturbance (van Dam, 2001; Ibrahima et al., 2002; Ibrahima et al., 2010) have been recognized to strongly influence plant litter decomposition rates. The relative importance of these factors varies according to the characteristics of the ecosystems under consideration (Lavelle et al., 1993; Trofymow et al., 2002).

Other significant variables that affect litter decomposition process are soil organisms, which are diverse and abundant (Carcamo et al., 2000; David and Gillon, 2002). Representatives of nearly all groups of terrestrial invertebrates are involved in litter decomposition and the subsequent release of nutrients (Carcamo et al., 2000; David and Gillon, 2002). Soil microorganisms (<0.2 mm; including bacteria, fungi, protozoa) are directly responsible for most litter decomposition, and soil macroorganisms (>2 mm; including termites, earthworms and macroarthropods) can stimulate decomposition via litter fragmentation and defecating into the soil, and through altering the activity and composition of the microbial communities (Wardle, 2002; Rawlins et al., 2006; Meyer et al., 2013). Soil faunal excretions like mucus and other substances provide particularly suitable substrates for microbial communities (Kautz and Topp, 2000; Lavelle and Spain, 2002; Wardle, 2002). By the processes of fragmentation and comminution, earthworms can influence litter decomposition through their pedological effects:

modification of soil structure through the construction of burrows and enhancing the decomposition of plant debris through the burial of leaves (Lavelle, 1988; Swift and Anderson, 1989). Madge (1965) showed that the earthworms affect litter decomposition not by pulling leaves into its galleries but by covering them with casts. Marinissen and Bok (1988) demonstrated that the activity of earthworms could lead to increases in the population size and abundance of Collembola. Brown (1995) asserted that the effect of earthworms on microorganisms could be a net reduction in their density and species diversity due to the competitiveness of the interaction.

The role of microorganisms in litter decomposition cannot be discussed without reference to their interactions with the soil fauna. Interactions between soil organism communities as earthworms and soil microorganisms in the litter decomposition process have been well studied for tropical forest and temperate ecosystems (Heemsbergen et al., 2004; Hättenschwiler and Gasser, 2005; Bastian et al., 2008; McKie et al., 2008; De Oliveira et al., 2010). However, little information was available for tropical savannahs and the complex interactions between soil fauna and microorganisms are less well understood (Adejuyigbe et al., 2006). The objective of the study was to determine the effects of earthworms and its relative synergistic effects with microorganisms on leaf-litter decomposition of six contrasting plant species of the sudano-guinea savannahs zone of Ngaoundere Cameroun.

MATERIALS AND METHODS

Study Area

The locality of this study lying within the Adamawa region located on 7°25'N and 13°33'E, with elevation of about 1081 m. The climate is humid sudano-guinea with two seasons: a long dry season (from November to March), rainy season (from April to October). Mean annual rainfall is about 1500 mm and mean annual temperature 23°C (Humbel, 1971). The soil in majority is red ferralitic developed on old basalt. The dominant vegetation is woody and shrubby Savannahs (Letouzey, 1968).

Leaf Selection
In this study, only fresh fallen leaf litter of six socio-economical plant species of the Sudano-guinea

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savannahs of Ngaoundere was used. The experiments involved six species: deciduous broad-leaved including four shrub species (*Annona senegalensis*, *Combretum molle, Syzygium guineense* var. *macrocarpum* and *Ximenia americana*) and an evergreen broad-leaved including one tree species (*Syzygium guineense* var. *guineense*) and a shrub species (*Anacardium occidentale*). The distribution area of *S. guineense* var. *guineense* (Willd) D.C. (Myrtaceae) is the forest gallery, while *A. occidentale* L. (Anacardiaceae), *A. senegalensis* Pes. (Annonaceae), *C. molle* R. Br. Ex G. Dom. (Combretaceae), *S. guineense* var. *macrocarpum* (Engl.) F. White (Myrtaceae) and *X. americana* L. (Olacaceae) are located in the upland Savannahs. They are source of income, food, firewood, medicinal substances and soil fertility indicators for the farmers of this region (Yonkeu, 1993; Ibrahima et al., 2007). The farmers start now to conserve these plant species in their farms and gardens. New litter fall samples were collected directly from forest floor in the Ngaoundere humid savannahs, next to the Dang campus of the University of Ngaoundere, Cameroon, during maximum leaf fall period (November 2006 – January 2007) that corresponds to dry season and soil was very dry. No leaching occurred from new litter which was sorted, air-dried and stored in the laboratory before use.

Leaf Litter Incubation Experiment

Study was carried out in microcosms at the constant laboratory conditions. Microcosm model used is of the type described by Taylor and Parkinson (1988) and as modified by Gillon et al., (1994). One kg of soil consisting of surface organic horizon from the Dang site was placed in each of microcosm. Characteristics of site including soil type were described earlier by Ibrahima et al., (2010). In order to get rid of lumps and vegetation remains, the soil was previously sieved at 1 mm to eliminate all meso- and macro-fauna then a part of it was sterilized during 24h by the dry heat method (Adejuyigbe et al., 2006).

In an attempt to determine the relative effects of the two types of soil organisms (earthworms and microorganisms) on litter decomposition rate, four different treatments were realized in similar incubation chambers : 1) microcosms containing only sieved and sterilized soil without earthworms (SS); 2) microcosms containing sieved and non-sterilized soil without earthworms (NS); 3) microcosms containing sieved and sterilized soil with common earthworms (SE) of the region and 4) microcosms containing sieved and non-sterilized soil with earthworms (NE). We assumed the sieved and non-sterilized soil containing soil microorganisms. The litter mass loss of microcosms containing only sieved and sterilized soil without earthworms (SS) was due to leaching.

For each treatment, ninety (90) samples of 7.00±0.01g of each of six litter types (*A. occidentale*, *A. senegalensis*, *C. molle*, *S. guineense* var. *guineense, S. guineense* var. m*acrocarpum* and *X. americana*) were weighed and placed on the soil top of microcosms and material of 2 mm mesh to recover all the material at each sampling time. The quantity of water needed to replace that evaporating and thus maintain constant soil moisture during incubation was also calculated each week by weighing the microcosms and adding. The microcosms were maintained at 23°C ± 1°C and a relative humidity of 68% ± 2% throughout the experiment.

Three samples of each species at each treatment were taken at 15, 30, 50, 70 and 120 days, and their dry mass determined by electrical balance *(Sartorius Type ISO-9001),* after drying in oven, *Memmert*, for 48 hours at 59°C. Three additional litter samples were weighed after drying in an oven at 59°C for 48 hours to determine the original litter dry mass. The litter dry mass remaining (LMR) as a percentage of the initial mass was calculated as following : LMR (%) = $(DM_t/DM_0) \times 100$ where, DM_t is dry mass at the sampling time t and DM_0, the initial dry mass.

The contribution of earthworms in presence (EM) and absence of microorganisms (EO) and that of soil microorganisms in presence (ME) and absence of earthworms (MO) were calculated as following:

EM = NE – NS; (Effects of earthworms in presence of soil microorganisms);
EO = SE-SS; (Effects of earthworms in absence of soil microorganisms)
ME = NE-SE; (Effects of soil microorganisms in presence of earthworms)
MO = NS-SS; (Effects of soil microorganisms in absence of earthworms)

SY = NE-SS   (Synergistic effects of earthworms and soil microorganisms)

For each species, three replicates of litter samples were oven-dried (48 h at 65°C), then weighed and their thickness measured by calliper. To avoid fragmentation, leaf litter was moistened again, spread out and then the leaf side length and maximum width were measured using millimeter paper. Litter area and surface mass (Gillon et al., 1994) or sclerophylly index (Choong et al., 1992) were calculated using respectively equation of Paynes et al., (1997) and, litter mass and area ratio :

A = 0.68 x (length x maximum width) – 0,114

SI = DM/A

Where, A, SI and DM are respectively leaf litter area (cm^2), sclerophylly index (mg.mm^{-2}) and dry mass of initial litter (g).

Chemical Analysis

The samples of initial dry litters were ground in *Micro Hamer Mill Culatti Blender* and sieved at 1 mm. The concentration of cellulose, phenolic compounds and lignin were respectively determined by colorimetric method (Updegraff, 1969), by Folin-Ciocalteu reagent (Marigo, 1973) and by van Soest's (1965) and detergent method.

Data Analysis

The litter dry mass remaining (LMR) of each species for each treatment in relation to litter incubation time (in days) was fitted to the following simple exponential model:

LMR = A*exp(-kt)

Where, k is the decomposition rate constant (%.day^{-1}), A the compartment of water soluble substances and other compounds. Because of the high significance of coefficients of determination, the equation was adoptee.

A multiple comparison among the decomposition rate constants (k) was carried out using the *T' - method* (Sokal and Rohlf, 1981) to compare for each species the effects of soil organisms (earthworms and microorganisms) on litter decomposition rate.

Using one-way ANOVA (species or soil organisms), following by *Scheffe*'s mean comparison test at 5% (if ANOVA was significant)

compared LMR among plant species and among treatments (SS, SN, SE and NE). ANOVA was also used to test the effects of treatments on LMR at each sampling time (15, 30, 50, 70 and 120 days). Two-way ANOVA (species and treatments) was used to compare the combined effects of litter types and treatments. Pearson's correlation coefficients were calculated between decomposition rate constants (k) and physico-chemical properties of initial litter. Simple and multiple (stepwise) regression models were also used to determine relationships between these parameters. These tests were conducted through software package SX for DOS, version 4.0. (Statistics, 1992).

RESULTS

Initial Litter Properties

All initial litter characteristics presented in this study differed significantly among plant species (Table 1). The highest values of litter thickness (0.78 mm) and area (58.98 cm^2) were found in *A. senegalensis* shrub and the lowest ones in *X. americana* shrub (0.34 mm and 22.78 cm^2). Sclerophyllous index (SI) varies significantly from *A. occidentale* (0.15 mg.mm^{-2}) to *A. senegalensis* (0.23 mg.mm^{-2}) and *X. americana* (0.25 mg.mm^{-2}). The organic compounds as cellulose (2.89%) and phenolic compounds (6.90%) were highest in *X. americana* and lowest respectively in *C. molle* (1.14%) and *A. senegalensis* (1.16%). The highest values of lignin were in *A. senegalensis* (6.03%) and the lowest one in *S. guineense* var. *guineense* (2.84%).

Changes in LMR during course of litter incubation time

The dynamics of LMR during 120 days of microcosms at constant conditions of laboratory were similar for all species at each treatment, except those of *X. americana* (Figure 1). The differences of LMR between *X. americana* and others species were started since the first sampling time (15 days) for both treatments with no sterilized soil and with and without earthworms (NE and NS).

The Changes of LMR differed significantly among treatments (Figure 2). From the second to the end sampling time, two types of patterns of LMR

Table 1. Physical and chemical properties of initial litters of six plant species of Ngaoundere savannahs of Cameroon.

Species	Thickness (mm)	Area (cm^2)	IS (mgmm^{-2})	Cellulose (%)	Lignin (%)	Phenol (%)
AO	0.43 (0.07)c	51.83 (14.20)ab	0.15 (0.05)b	ND	ND	ND
AS	0.78 (0.10)a	58.98 (19.46)a	0.23 (0.08)a	2.02 (0.06)ab	6.03 (0.69)a	1.16 (0.02)e
CM	0.62 (0.09)b	42.97 (11.35)b	0.18 (0.06)ab	1.14 (0.41)b	5.34 (0.78)ab	2.62 (0.09)d
SG	0.56 (0.10)b	29.10 (8.36)c	0.20 (0.06)ab	1.57 (0.25)ab	2.84 (0.68)b	4.79 (0.35)b
SM	0.39 (0.06)c	49.75 (14.70)ab	0.21 (0.08)ab	1.80 (0.19)ab	5.77 (0.74)ab	3.66 (0.01)c
XA	0.34 (0.03)c	22.78 (5.21)c	0.25 (0.06)a	2.89 (0.48)a	4.65 (0.12)ab	6.90 (0.23)a
F	90.36***	22.57***	6.06**	8.34*	7.75*	1014.07***

* $p < 0.05$, ** $p < 0,01$, ***$p < 0,001$. Numbers in parentheses indicate standard deviation. Non determined value (ND). Different letters indicate significant differences among different species : *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense* var.*guineense* (SG), *S. guineense* var. *macrocarpum* (SM) and *X. americana* (XA).
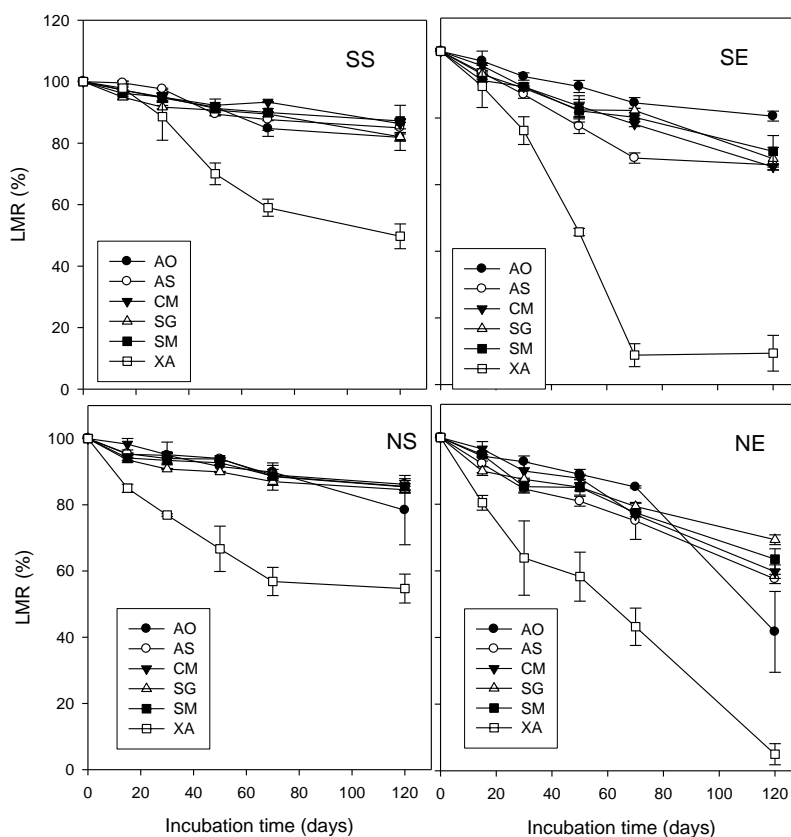

Figure 1. Changes of LMR of six species at each of four treatments (SS, NS,NE and SE) during the course of incubation time in laboratory microcosms. Non sterilized soil without earthworms (NS), sterilized soil without earthworms (SS), non sterilized soil with earthworms (NE), sterilized soil with earthworms (SE). *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense.* var. *guineense* (SG), *S. guineense.* var. *macrocarpum* (SM) and *X. americana* (XA).
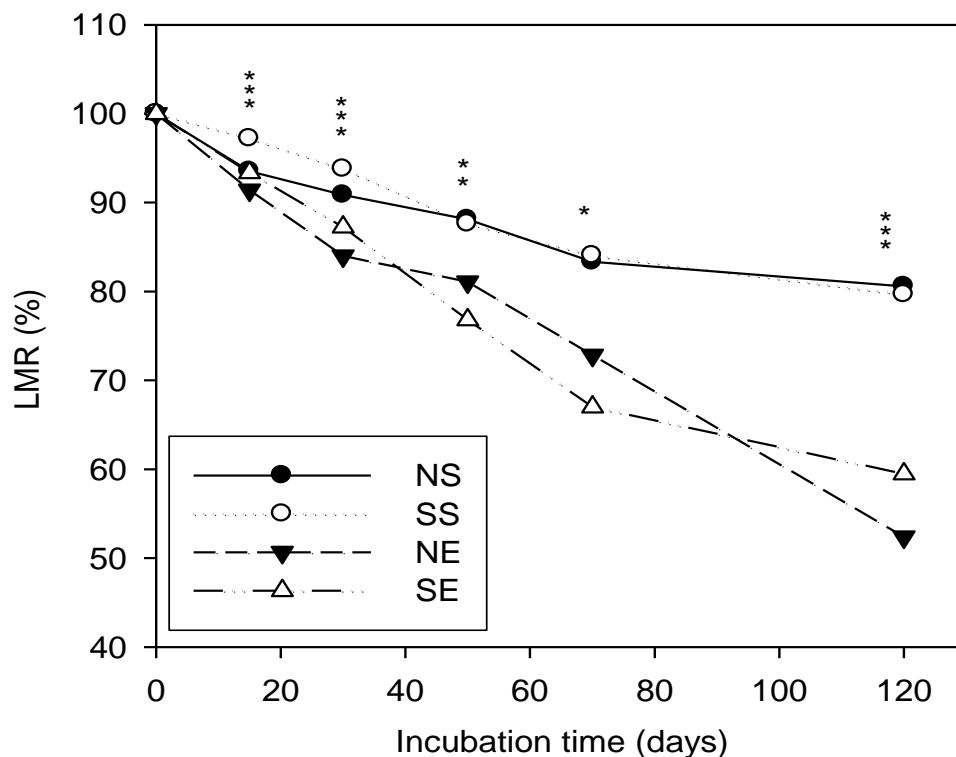
Figure 2. Changes of LMR mean of six species of treatments with (NE and SE) and without (SS and NS) earthworms during the course of incubation time in laboratory microcosms. * p<0.05, ** P<0.01 and *** P<0.001. Non-sterilized soil without earthworms (NS), sterilized soil without earthworms (SS), non-sterilized soil with earthworms (NE), sterilized soil with earthworms (SE).

changes were found. The LMR for the treatments with earthworms (SE and NE) were significantly low than those of treatments without earthworms (SS and NS) during course of incubation time. In each group, the patterns of LMR changes were similar. The patterns of LMR of the treatments for each species were presented in Figure 3. According to treatments, three groups of species were found. The group constituted by *A. occidental s*howed no significant difference of LMR changes among four treatments, except at the last sampling time (120 days) where the LMR for the only treatment with no sterilized soil containing earthworms (NE) was significantly low than the three others treatments. For the second group including all the remaining species, LMR for the treatments with earthworms (SE and NE) were significantly low than those of treatments without earthworms (SS and NS) during course of incubation time.

The LMR was fitted to negative exponential model, with highly significant coefficient of correlation at all species and all treatments (Table 2). A multiple comparison of decomposition rate constants (k) by *T'-method* (Sokal and Rohlf, 1981) showed that the decay rates varied among species and among treatments (Figure 4). *X. americana* had higher decomposition rate constant than the five others species for all the treatments. The decomposition rate constants of all species for both the treatments without earthworms (SS and NS) were similar and lower than those of both the treatments with earthworms which were not differed between them. That of *A. occidentale* was significantly higher for the treatment with no sterilized soil containing earthworms (NE) than those of other litter. For all species, the decomposition rate constants for treatments with earthworms were significantly higher than for treatment without earthworms, excepting
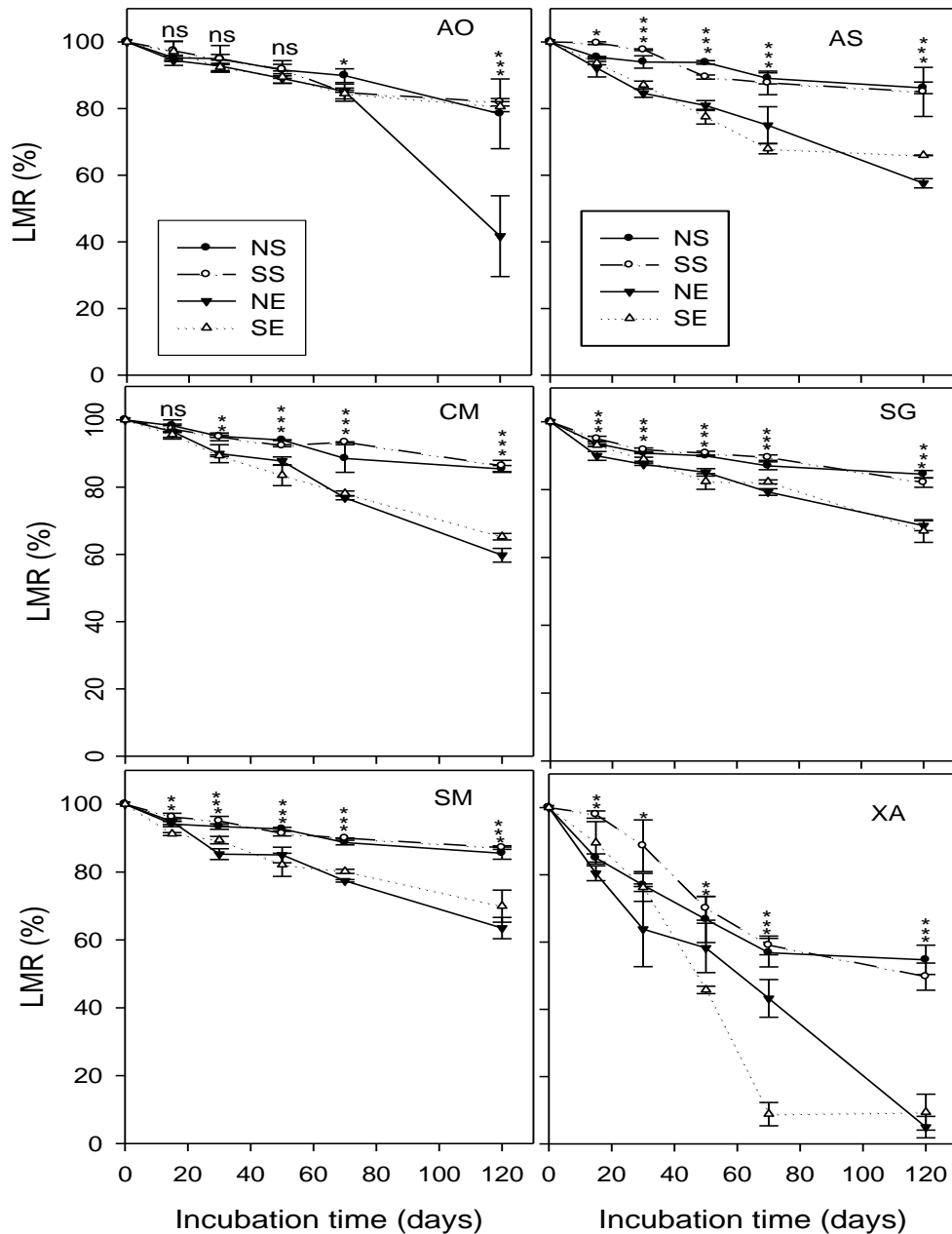
Figure 3: Changes of LMR (%) of each of six species for four treatments during the course of incubation time in laboratory microcosms. ns, non-significant, * p<0.05, ** P<0.01 and *** P<0.001. Non-sterilized soil without earthworms (NS), sterilized soil without earthworms (SS), non sterilized soil with earthworms (NE), sterilized soil with earthworms (SE). *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense.* var. *guineense* (SG), *S. guineense.* var. *macrocarpum* (SM) and *X. americana* (XA).

that of *A. occidentale* for treatment sterilized soil containing earthworms (SE) which was statistically

similar with those for both treatments without earthworms (SS and NS).

Table 2. Coefficient of correlations (R) of exponential regression equations (y = exp (-kt)) describing changes in LMR with incubation time (in days). All are highly significant at P< 0.001, n = 18 or * n = 17.

Species	SS	NS	SE	NE
A. occidentale	0.9476	0.8511	0.9587	0.8713
A. senegalensis	0.8785*	0.9368*	0.9580*	0.9806
C. molle	0.9549	0.9385	0.9944	0.9794
S. guineense . var. guineense	0.9642	0.9126	0.9775	0.9758
S. guineense. var. macrocarpum	0.9476*	0.9368	0.9629	0.9803
X. americana	0.9592*	0.9382*	0.9467	0.9570

Sterilized soil (SS), non sterilized soil (NS), sterilized soil with Earthworms (SE) and non sterilized soil with Earthworms (NE)
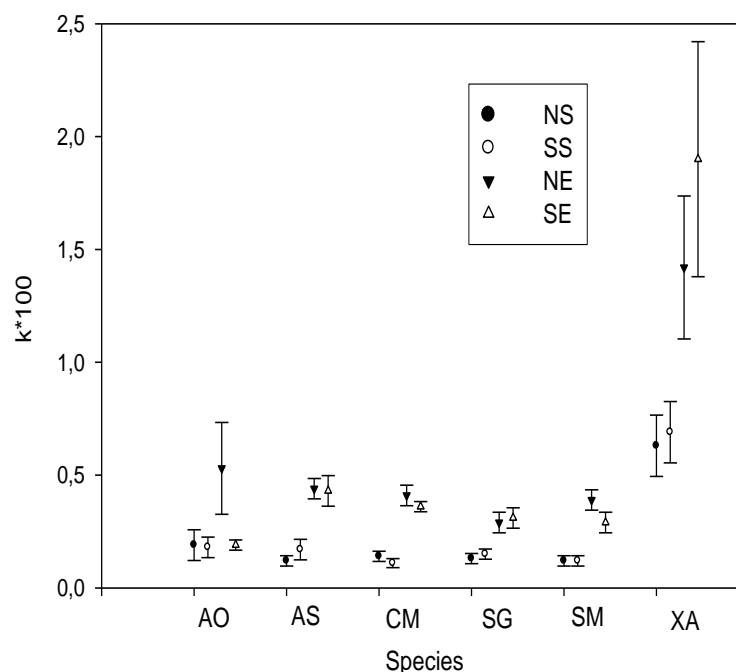

Figure 4. Decomposition rates constant (k) of 6 species for each treatment after 120 days of litter incubation laboratory microcosms. Treatments: non sterilized soil (NS) and sterilized soil (SS) without earthworms; non sterilized soil with earthworms (NE) and sterilized soil with earthworms (SE). *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense.* var. *guineense* (SG), *S. guineense.* var. *macrocarpum* (SM) and *X. americana* (XA).

LMR at the last sampling date

At each of four treatments, litter types (or species) differed significantly by their LMR at the end of incubation (120 days) in microcosms (Table 3). The LMR varied from 49.71% in *X. americana* to 87.21%

Table 3. Litter mass remaining (LMR in %) at the end of incubation time (120 days) of the six species (AO, AS, CM, SG, SM and XA) at each of the four treatments (SS, NS, SE and NE).

Species	SS	NS	SE	NE	F (Treatments)
AO	81.89 (1.12)a α	78.40 (10.47)a α	80.56 (1.5)a α	41.69 (12.12)c β	17.27***
AS	84.98 (7.35)a α	86.20 (1.72)a α	65.95 (0.11)b β	57.57 (1.38)b β	50.90***
CM	86.33 (1.66)a α	85.41 (1.01)a α	65.28 (0.96)b β	59.75 (2.03)ab δ	254.22***
SG	82.07 (1.40)a α	84.55 (1.07)a α	67.81 (3.34)b β	69.34 (1.47)a β	53.83***
SM	87.21 (0.52)a α	85.58 (1.79)a α	69.98 (4.73)b β	63.50 (3.13)abβ	36.27***
XA	49.71 (4.03)b α	54.69 (4.37) b α	9.39 (5.30)c β	4.96 (6.17)d β	58.27***
F (Species)	46.51**	14.16***	161.25***	49.72***	

** $P<0.001$, ***$P<0.001$. Numbers in parentheses indicate standard deviation. Different arabic letters in columns indicate significant differences among different species. Different Greek letters in rows indicate significant differences among treatments (SS, NS, SE and NE). *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense* var. *guineense* (SG), *S. guineense* var. *macrocarpum* (SM) and *X. americana* (XA). Sterilized soil (SS), non sterilized soil (NS), sterilized soil with Earthworms (SE) and non sterilized soil with Earthworms (NE).

in *S. guineense* var. *macrocarpum* for the treatment with sterilized soil and without earthworms (SS), from 54.69% in *X. americana* to 86.20% in *A. senegalensis* for treatment with no sterilized soil and without earthworms (NS), from 9.39% in *X. americana* to 80.56% in *A. occidentale* for the treatment with sterilized soil and earthworms (SE) and from 4.96 in *X. americana* to 69.34% in *S. guineense* var. *guineense* for the treatment with no sterilized soil and earthworms (NE). Globally, litter mass loss was the significantly highest in *X. americana* for both treatments with earthworms (SE and NE), that of litter of *A. occidentale* for treatment with sterilized soil and earthworms (SE) and that of *S. guineense* var. *guineense* litter for treatment with no sterilized soil and earthworms (NE) were the lowest. On contrary, for treatment without earthworms (SS and NS), litter mass loss of *X. americana* was higher than those of the five others species which did not differ significantly among them. Two-ways ANOVA showed that combined effects of species and treatments was high significant (F= 10.93 and P<0.001) on LMR at the end of incubation time (120 days).

Contribution of soil organisms

Relative contributions of earthworms, microorganisms and litter leaching to litter mass loss were illustrated by Figures 5a; b and c. Litter mass loss for treatment with sterilized soil and without earthworms (SS) would correspond to litter leaching. The percentage of leaching of the six species varied from 12.79% in *S. guineense* var. *macrocarpum* to 50.29% in *X. americana* (Figure 5a). This leaching was significantly higher in *X. americana* than the other five species which happened to be similar among them.

The contribution of earthworms without and with microorganisms to litter decomposition varied according to species (Figure 5a and b). This relative contribution without microorganisms (EA) ranged from 1.34% in *A. occidentale* to 40.23% of litter mass loss in *X. americana* (Figure 5a). On the contrary, with the presence of microorganisms (EM), the relative contribution of earthworms to litter decomposition increased for all species, particularly for *A. occidentale* where it passed from 1.34% for earthworms alone (EA) to 36.71% for earthworms with organisms (EM).

The effects of microorganisms without earthworms (MA) appeared only in *C. molle, S. guineense* var. *macrocarpum* and *A. occidentale*, with low rate values of 0.92%, 1.63% and 3.50% respectively (Figure 5a). On the contrary, with presence of earthworms, the relative effects of microorganisms on litter decomposition appeared for all species with sometime the high values, except for *S. guineense*
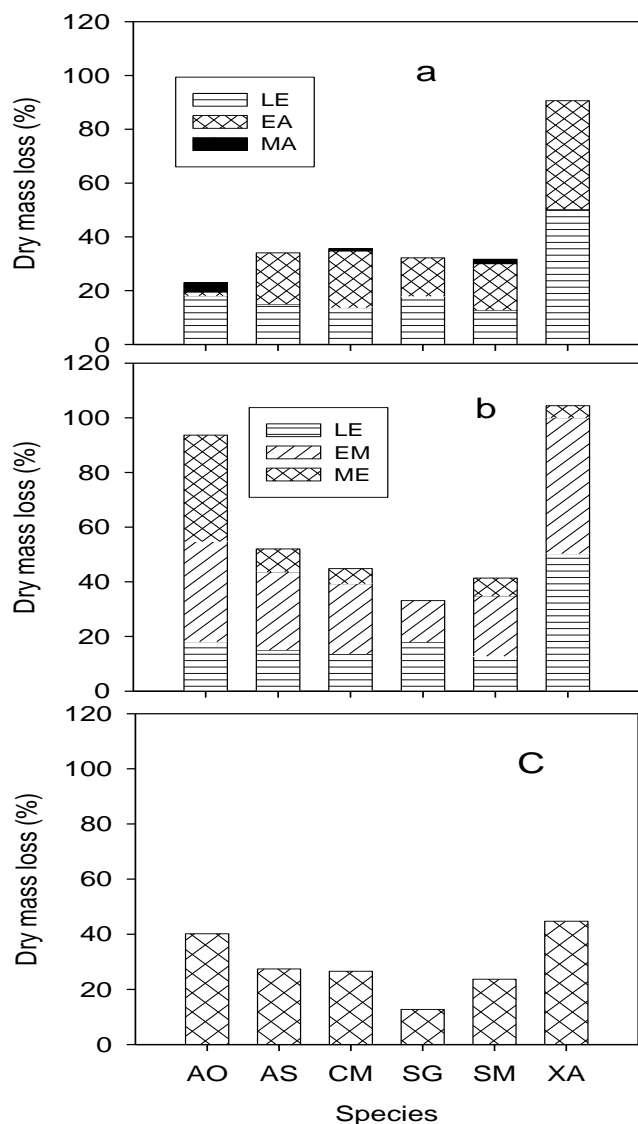
Figure 5. Relative contributions of leaching, earthworms and microorganisms to litter decomposition after 120 days of litter incubation laboratory microcosms.
a: Litter leaching (LE), effects of Earthworms alone (EA) and microorganisms alone (MA). b :Effects of earthworms in presence of microorganisms (EM) and effects of microorganisms in presence of Earthworms (ME); c: synergic effects. *A. occidentale* (AO), *A. senegalensis* (AS), *C. molle* (CM), *S. guineense.* var. *guineense* (SG), *S. guineense.* var. *macrocarpum* (SM) and *X. americana* (XA).

var. *guineense* (Figure 5b).The contribution of microorganisms to litter decomposition of *A. occidentale* for example was 10 times higher with

the presence of earthworms (38.87%) than without earthworms (3.50%). The relative contribution of microorganisms with earthworms ranged from 4.43% in *X. americana* to 38.87% in *A. occidentale.* Synergistic effects of earthworms and microorganisms to litter decomposition differed among species (Figure 5c), with the values ranged from 12.73% in *S. guineense* var. *guineense* to 44.75% in *X. americana*. The synergistic effects of microorganisms and earthworms were not the sum of individual effects of both the soil organism groups.

Correlation between LMR, decomposition rate constant and initial litter properties

Relationships between LMR at the end of incubation time and initial litter properties varied according to treatment (Table 4). For each of the four treatments, LMR after 120 days of incubation was correlated significantly and negatively with phenolic compounds. On the contrary, no significant correlation was found between LMR and lignin for each of four treatments. For sclerophyllous index (SI), LMR was correlated negatively with it only at the treatment with sterilized soil containing earthworms (SE). It was found that LMR was correlated positively with thickness only at the treatments with microorganisms (NS and NE).
Pearson coefficient correlations showed relationships between litter decomposition rate constants (k) and the mean values of initial litter properties (Table 5). These relationships varied according to treatments. Phenolic compounds were correlated significantly and negatively with litter decomposition rate constants (k) only at the treatments with earthworms (SE and NE). For the treatment with sterilized soil and without earthworms (SS), there were no significant correlations between litter decomposition rate constants (k) and the initial litter properties. On the contrary, for the others treatments (NS, SE and NE), the significant correlation were observed. For the treatment with no sterilized soil and earthworms (NE), k was correlated significantly with three initial litter properties, one physical (litter area) and two chemical (lignin and phenolic compounds). For each of the remaining treatments (NS and SE), k was correlated significantly with two initial litter properties, one physical and one chemical, that is

Table 4. Simple linear regression equations between LMR at the end of incubation time (120 days) and initial litter properties (Thickness, area, sclerophyllous index, cellulose, lignin and phenolic compounds) at each of the four treatments (SS, NS, SE and NE).

Treatments	Linear regressions equations	R^2	N	F
	LMR = 57.769+42.088*Thickness	0.2441	17	4.20ns
	LMR = 53.319 + 0.6166*Area	0.3936	17	8.44*
SS	LMR = 100.18 + 106.92*SI	0.0704	17	0.98ns
	LMR = 112.882 – 19.268*Cellulose	0.7021	8	14.14**
	LMR = 107.374 – 7.288*Phenolic Compounds	0.7808	8	21.37**
	LMR = 70.363 + 1.446*Lignin	0.010	8	0.06ns
	LMR = 62.166 +34.806*Thickness	0.2523	17	5.06*
	LMR = 62.371+0.4185*Area	0.2703	17	5.56*
NS	LMR = 100.38-98.160*SI	0.1373	17	2.39ns
	LMR = 103.43 – 12.240*Cellulose	0.4109	9	4.88ns
	LMR = 94,220 – 3.473*Phenolic Compounds	0.4676	9	6.15*
	LMR = 78.693 + 0.7082*Lignin	0.111	9	0.08ns
	LMR = 27.887+62.1594*Thickness	0.1478	17	2.60ns
	LMR = 9.2950+1.1908*Area	0.4646	17	13.02**
SE	LMR = 141.55-410.12*SI	0.4440	17	11.98**
	LMR = 109.505 – 27.918*Cellulose	0.6015	9	12.08**
	LMR = 89.482 – 8.523*Phenolic compounds	0.5503	10	9.79*
	LMR = 45.820 + 2.252*Lignin	0.0152	10	0.12ns
	LMR = 11.329+73.541*Thickness	0.2619	18	5.68*
	LMR = 19.352 – 0.7085*Area	0.1836	18	3.60ns
NE	LMR = 81.068 + 156.17*SI	0.0750	18	1.30ns
	LMR = 111.421 – 31.751*Cellulose	0.7144	9	20.03**
	LMR = 81.922 – 7.933* Phenolic Compounds	0.4377	10	6.23*
	LMR = 56.262 – 0.946*Lignin	0.0025	10	0.02ns

ns : non-significant, * P<0.05; ** P<0.01; ***P<0.001. Sterilized soil (SS), non sterilized soil (NS), sterilized soil with Earthworms (SE) and non sterilized soil with Earthworms (NE).

sclerophyllous index and cellulose for treatment with no sterilized soil and without earthworms (NS) and, thickness and phenolic compounds for treatment with sterilized soil and earthworms (SE).

The stepwise model showed the relationships between LMR at the end of litter incubation and associations of initial litter parameters at each of the four treatments (Table 6). The relationships between LMR and initial litter properties was explained more than 86% by the association of three chemical parameters (lignin, cellulose and phenolic compounds) and one physical parameter (sclerophyllous index) for both the treatments with soil microorganisms (NS and NE) or two physical parameters (sclerophyllous index and thickness) for the treatments without soil microorganisms and with earthworms (SE). In reverse, for the treatments without earthworms and soil microorganisms (SS), this relationship was explained about 95% by the association of one chemical parameter (lignin) and three physical parameters (sclerophyllous index, thickness and area).

DISCUSSION

Many studies reported on the synergistic effects of earthworms and other soil organisms including

Table 5. Correlation coefficient of Pearson (n=5) calculated between litter decomposition rate constants (k) and initial litter properties (Thickness, area, sclerophyllous index, cellulose, lignin and phenolic compounds) at each of the four treatments (SS, NS, SE and NE). In bold significant (P< 0.05 or P<0.01) correlations.

Parameters	SS	SV	NS	NV
Thickness (mm)	0,6367	0,9510	0,0810	0,4146
Area (cm^{-2})	0,2197	0,6163	-0,5690	0,9190
Sclerophyllous index (g mm^{-2})	0,7850	0,4235	-0,9199	0,3079
Cellulose (%)	0,7215	0,2631	-0,9693	0,2150
Lignin (%)	-0,1351	0,4595	-0,3483	0,9599
Phenolic compounds (%)	-0,3019	-0,9051	0,1933	-0,9193

Sterilized soil (SS), non-sterilized soil (NS), sterilized soil with Earthworms (SE) and non sterilized soil with Earthworms (NE).

Table 6. Multiple regressions (Stepwise) between LMR at the end of incubation time (120 days) and initial litter properties (Thickness, area, sclerophyllous index, cellulose, lignin and phenolic compounds) at each of the four treatments (SS, NS, SE and NE).

Treatments	Stepwise regression equations	R^2	n
NS	LMR = 74.519 – 4.501*lignin + 3.969*Cellulose – 3.301* Phenol + 27.221*SI	0.9159	9
SS	LMR = 122.787 – 6.467*Lignin – 354.496*SI + 48.723*Thickness + 0,702*Area	0.9533	8
NV	LMR = 65.180 – 12.658*Lignin + 8.678*Cellulose – 7.280*Phenol + 100.200*SI	0.8658	10
SV	LMR = 85.725 – 11.202*Lignin + 7.897*Cellulose – 11.034*Phenol + 113.237*SI– 44.946*Thickness	0.8828	10

Sterilized soil (SS), non sterilized soil (NS), sterilized soil with Earthworms (SE) and non sterilized soil with Earthworms (NE).

microbes and fungi on litter decomposition process in terrestrial and aquatic ecosystems (Lussenhop, 1992; Suberkropp, 1992; Jonsson and Malmqvist, 2000; Wall et al., 2001; Heemsbergen et al., 2004; Hättenschwiler and Gasser, 2005; Hättenschwiler et al,. 2005; Tiunov and Scheu, 2005; Zimmer et al,. 2005; Duffy et al., 2007; Cardinale et al., 2009; Reiss et al., 2009; Rotheray et al,. 2009; Leon and Nelson, 2014; Parsons et al., 2014; Suseela et al., 2013; Dhanya et al., 2013; Bothwell et al., 2014). But the synergistic contribution of microorganisms and earthworms in leaf litter decomposition process in African Savannah has been rarely studied with, our knowledge, only an exception of Adejuyigbe et al., (2006) who asserted positive effects of the interaction of microarthropods and earthworms on the litter decomposition of *Senna siamea* in Savannah of Nigeria. The value reported in their study was about 61% of initial mass loss. After 120 days of six contrasting and co-occurring litter incubation in microcosms in our study, our findings have shown that the mass loss during litter decomposition in microcosms was higher with both soil organisms presence than with either earthworms nor soil microorganisms alone present. The value of this synergistic contribution varied from 12.73 to 44.75% of mass loss according to litter type. The difference between the results of two studies was due to difference of the methodology and litter quality. In fact, the microcosms in their study were consisting of Oxic Paleustaff soil (red earth) (USDA) and contained six individual of Earthworms (*Hyperiodrilus sp.*) and microarthropods. Conversely, in our study, the microcosm soil was constituted of ferralitic soil (Humbel, 1971) and containing microorganisms and 4 individual of earthworms (*Lombricus sp.*). The litters used under both studies differed also by their

quality. *Senna siamea* litter was higher in lignin (9%) and lower of polyphenols (1.78%) concentrations than those of litters used in our study (lignin concentrations varied from 2.84 to 6.03% and polyphenols compounds from 1.16 to 6.90%). Others synergistic interactions among different species of litter feeding animals have also been observed for three Plecoptera (insects) species in an aquatic ecosystem (Jonsson and Malmqvist, 2000), for eight different soil macrofauna species (Heemsbergen et al., 2004), for the combination of an earthworm and an isopod species (Zimmer et al., 2005), and for complementarily of snail and millipede in the Mediterranean forest (De Oliveira et al., 2010). All these studies were done in controlled laboratory conditions like our study. The rare published field study manipulating macrofauna presence has shown no synergistic effects between *Glomeris* spp. and anecic earthworm species exposed to a range of different litter species and mixtures (Hättenschwiler and Gasser, 2005).

Soil fauna largely control the decomposition process through breakdown of litter, digestion, and stimulation of micro-organism activities (Byzov et al., 1996; Maraun and Scheu, 1996). In line with above findings, our study demonstrated that relative contributions of soil microorganisms (<1mm) and earthworms to litter decomposition process were significant and varied according to plant species. Indeed, the decompositions of 6 litters in the 2 earthworm-free treatments (SS and NS) do not differ significantly amongst them for all species. This suggests that the action of microorganisms alone on the litter decomposition, that is, their contribution in the absence of earthworms is very low for all species (Figure 5a). On the other hand, in the presence of earthworms, this contribution of microorganisms to the litter decomposition is wholly significant for the 6 litters. This confirms that the action of microorganisms would be tributary of that of the soil macrofauna just like termites and earthworms. Similarly, concerning the two treatments with earthworms (SV et NV), the mass loss of litters is significantly higher on the normal soil with earthworms than on the sterilized soil with earthworms, except for litter of *S. guineense* var. *guineense* and *X. americana*. For these two litters, the presence of microorganisms of the soil does not significantly increase the action of earthworms. These results suggest on the one hand that while

the action of earthworms is important at the beginning of the litter decomposition, it must be completed by that of microorganisms including microbes and mushrooms in order to ensure a mineralization of nutrients and, on the other hand, these synergistic actions depend on the type of litter. It is clear that earthworms and microorganisms play synergistic roles in litter decomposition process and this could be attributed to differences in their functional dissimilarity (Heemsbergen et al., 2004; Gessner et al., 2010). In fact, the macrofauna just like earthworms start by fragmenting the litters, then expand their surface thereby allowing an easier access of microorganisms and microbes into the cells of leaves for the degradation of organic molecules (Swift et al., 1979; Adejuyigbe et al., 2006; De Oliveira et al., 2010). Other studies have also shown that earthworms can promote microbial abundance, diversity and activities by facilitating mechanisms that are:1) fracturing litter, thereby increasing the surface area available to microbes, 2) increasing available nutrients through waste production and mucus secretion, 3) consuming microbes, which can lead to vigorous microbial growth, 4) modifying the habitat in ways that facilitate microbial growth/activity and 5) modifying the habitat in ways that increase recruitment of other smaller invertebrates (i.e. <2mm) that can influence litter decomposition by the four previous mechanisms (Belovsky and Slade, 2000; Cardinale et al., 2007; Eisenhauer et al., 2007; De Oliveira et al., 2010). Unlike for microorganisms, it seems that the soil macrofauna just like termites and earthworms would not possess the necessary enzymes to directly degrade the organic compounds of the soil like the lignin, the tannin and the humic complex of the soil. Such enzymes would be produced by microorganisms and mushrooms and, allow these macrodetritivores to assimilate compounds and nutrients resulting from the fragments of ingested litters (Cardinale et al., 2007; De Oliveira et al., 2010; Crowther et al., 2012). Other possible explanation given by Gessner et al., (2010) is that colonization of leaf litter by palatable fungal species can render even relatively refractory leaf species attractive to macrodetritivores and stimulate consumption, as indicated by experiments in both terrestrial and aquatic ecosystems (Mulder et al., 1999; Lecerf et al., 2005; Hättenschwiler and Gasser, 2005; Bastian et al., 2008). These

mechanisms, so called facilitation and resource partitioning, are widely discussed in the literature of plant diversity effects on net primary production and are thought to contribute to complementary in more diverse plant communities (Cardinale et al., 2007). It is notoriously difficult to separate these mechanisms (van Ruijven and Berendse, 2003; Roscher et al., 2008) and it is likely all contributed to the observed increased litter mass loss in our study.

The synergistic effect of earthworms and other soil organisms such as microorganisms, microbes and mushrooms on the litter decomposition process varies according to the type of litters (Figure 3c). This effect is stronger on litters with low thickness and rich in cellulose (Table 1) and with high capacity to release water soluble substance (Ibrahima et al., 2003) as *X. americana* (44,75%) and *A. occidentale* (40,20%). Moreover, the synergistic value is lower than the sum of individual values of earthworms and soil microorganisms for all species. These results suggested that the physical features of leaf-litter as litter thickness, as well as their chemical quality as lignin and polyphenols seemed generally to play a great role in the faunal effects on litter decomposition process as reported by De Oliveira et al., (2010), Cleveland et al., (2002, 2006) and Kaspari and Yanoviak (2008) in tropical Forests. From their field study on sixteen co-occurring tropical rain forest tree species of French Guiana, Coq et al., (2010) suggested that animals feeding preferences among litter specie were apparently essential driven by litter condensed tannins concentration. Mechanisms similar to those proposed for the anti-herbivore effects of tannins may explain the avoidance of tannin-rich litter by soil animals. These potentially include toxicity or deterring effects (Poinsot-Balaguer et al., 1993) and tannin binding with dietary proteins or digestive enzymes (Feeny, 1969). In contrast to the negative correlation with litter condensed tannin, the fauna effect increased with increasing litter hemicelluloses and cellulose concentrations (Coq et al., 2010). We found significant ($P < 0.05$) correlations between the remaining mass loss and polyphenol with and without presence of earthworms and microorganisms, and this remaining mass loss correlated also with litter thickness in treatment with microorganisms presence. However, as concerns the other physico-chemical characteristics of litters like the cellulose and the lignin, this correlation varies according to the type of treatment. But it is noteworthy that the phenolic compounds, the lignin and the cellulose could not be determined in all litters, and this could shadowed the quality effect of the litter on the synergistic action of functional groups of soil organisms on the litter decomposition as per our research.

CONCLUSION

In conclusion, as far as we know, this study indicated that interaction of earthworms and microorganisms provided a significant contribution to decomposition of litters of different co-occurrence tree species of Ngaoundere savannahs used in this study. These explained by complementarily activities of functional dissimilarity of soil organism communities and varied according to physical features of litter as well as their chemical quality. This research holds implication for the importance of preserving all soil fauna diversity in the sudano-guinea savannahs of Ngaoundere Cameroon for assuring efficiently nutrient cycling and contributing to soil fertility management.

REFERENCES

Adejuyigbe CO, Tian G, Adeoye GO (2006). Microcosmic study of soil microarthropod and earthworm interaction in litter decomposition and nutrient turnover. Nutr. Cycl. Agroecosys., 75: 47 –55.

Bastian M, Pearson RG, Boyero L (2008). Effects of diversity loss on ecosystem function across tropic levels and ecosystems: a test in a detritus-based tropical food web. Aust. Ecol., 33: 301-306.

Belovsky GE, Slade JB (2000). Insect herbivory accelerates nutrient cycling and increases plant

production. Ecology, 97(26): 14412-14417.

Bothwell LD, Selmants PC, Giardina CP, Litton CM (2014). Leaf litter decomposition rates increase with rising mean annual temperature in Hawaiian tropical montane wet forests. Peer J., 2: 41-51.

Brown GG (1995). How do earthworms affect microflora and faunal community diversity. Plant Soil, 170: 209-231.

Byzov BA, Chernjakovskaya TF, Zenova GM, Dobrovolskaya TG (1996). Bacterial communities associated with soil diplopods. Pedobiologia, 40: 67–79.

Carcamo HA, Abe TA, Prescott CE, Holl FB, Chanway CP (2000). Influence of millipedes on litter decomposition, N mineralization, and microbial communities in a coastal forest in British Columbia, Canada. Can. J. Forest Res., 30(5): 817-826.

Cardinale BJ, Srivastava DS, Duffy JE, Wright JP, Downing AL, Sankaran, Jouseau C (2006). Effects of biodiversity on the functioning of trophic groups and ecosystems. Nature, 443: 989-992.

Cardinal BJ, Duffy JE, Srivastava DS, Loreau M, Thomas M (2009). Towards a food web perspective on biodiversity and ecosystem functioning. In *Biodiversity, Ecosystem Functioning, and human wellbeing: an ecological and economic perspective*. Ed. Naeem S, al.,p. 105-120.

Cardinal BJ, Wright JP, Cadotte MW, Carrolt IT, Hector A, Srivastava DS, Loreau M, Weis JJ (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. P. Nat. Acad. Sci. 104: 18123-18128.

Choong MF, Lucas PW, Ong JSY, Pereira B, Tan HTW, Turner IM (1992). Leaf fracture-toughness and sclerophylly: their correlations and ecological implications. New Phytol., 121: 597-610.

Cleveland C, Alan RT, Steven KS (2002). Phosphorus limitation of microbial processes in moist tropical forests: evidence from short-term laboratory incubations and field studies. Ecosystems, 5: 680-691.

Cleveland CC, Reed SC, Townsend AR (2006). Nutrient regulation of organic matter decomposition in a tropical rain forest. Ecology, 87: 429-503.

Coq S, Souquet JM, Meudec E., Cheynier V (2010). Interspecific variation in leaf litter tannins drives décomposition in a tropical rain forest of French Guiana. Ecology 91(7): 2080-2091.

Crowther TW, Boddy L, Jones TH (2012). Functional and ecological consequences of saprotrophic fungus-grazer interactions. The Int. Soc. Microb. Ecol., 6: 1992-2001.

David JF, Gillon D (2002). Annual feeding rate of the millipede Glomerismarginata on holm oak (Quercus ilex) leaf litter under Mediterranean conditions. Pedobiologia 46: 42-52.

De Oliveira T, Hattenschwiler S, Handa IT (2010). Snail and millipede complementarity in decomposing Mediterranean forest leaf litter mixtures. Funct. Ecol., 24: 937-946.

Dhanya B, Viswanath S, Purushothaman S (2013). Decomposition and Nutrient Release Dynamics of *Ficusbenghalensis* L. ISRN Forestry, 2013: 1 -7.

Duffy J, Cardinale BL, France KE, McIntyrePB, Thiebault E, Loreau M (2007). The functional role of biodiversity in ecosystems: incorporating tropic complexity. Ecol. L., 10: 522-538.

Eisenhauer N, Partsch S, Parkinson D, Scheu S (2007). Invasion of a deciduous forest by earthworms: changes in soil chemistry, microflora, microarthropods and vegetation. Soil Biol. Biochem., 39: 1099-1110.

Elser JJ, Bracken MES, Cleland EE, Gruner DS, Harpole WS, Hillebrand H, Ngai JT, Seabloom EW, Shurin JB, Smith JE (2007).. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol. L., 10: 1135-1142.

Feeny PP (1969). Inhibitory effect of oak leaf tannins on the hydrolysis of proteins by trypsin. Phytochemistry, 8 : 2119-2126.

Gessner MO, Swan CM, Dan C, Mckie BG, Bardgett RD, Wall DH, Hattenschwiler S (2010). Diversity meets decomposition. Trend. Ecol. Evol., 25(6): 372-380.

Gillon D, Joffre R, Ibrahima A (1994). Initial litter properties and decay rate: a microcosm experiment on Mediterranean species. Can. J. Bot., 72: 946-954.

Hättenschwiler S, Gasser P (2005). Soil animal alter plant litter diversity effects on decomposition. Proc. Nat. Acad. Sci.,102: 1519-1524.

Hättenschwiler S, Tiunov AV., Scheu S (2005). Biodiversity and litter decomposition in terrestrial ecosystems, Annu. Rev. Ecol. Evol. Syst. 36: 191-218.

Heemsbergen DA, Berg MP, Loreau M, Van Ha, JR., Faber JH, Verhoef HA (2004). Biodiversity effects on soil processes explained by interspecific functional dissimilarity. Science, 306: 1019-1020.

Humbel FX (1971). Carte pédologique de Ngaoundéré 10 a 1/50 000. Centre de Yaoundé, Cameroun, ORSTOM. Note Explicative, 118P+Carte.

Ibrahima A, Abib Fanta C, Ndjouenkeu R, Ntoupka M (2010). Impact de la gestion de la matière organique sur le statut minéral des sols et des récoltes dans les savanes soudano-guinéennes de Ngaoundéré Cameroun. Proceeding of Actes du colloque, PRASAC, PP 1-10.

Ibrahima A, Nguetnkam JP, Hamawa, Y, Todou G, Wanyaola B, Doba R (2003). Dynamique d'imbibition et de lessivage des litières de neuf espèces à usages multiples des savanes soudano-guinéennes de l'Adamaoua, Cameroun. J. Cameroon Acad. Sci., 3(1): 35-45.

Ibrahima A, Nguetnkam JP, Pabamé P, Beunon T, Guidawa G (2007). Soil degradation in the Sudano-guinea savannas of Mbe, Cameroon : farmers' perception, indicators and soil fertility management stratégies. Res. J. Agric. Biol. Sci., 36(6): 907-916.

Ibrahima A., Ntonga JP, Mvondo Ze AD (2010). Leaf litter decomposition in tropical rainforest of Ebom, southwest Cameroon: comparison among guild classes. Trop. Ecol., 51 (2): 125-132.

Ibrahima A, Schmidt P, KetnerP, Mohren GJM (2002).Phytomasse et cycle des nutriments dans la forêt tropicale dense humide du sud Cameroun. Tropenbos-Cameroon Documents 9, Kribi, Cameroun.

Jonsson M, Malmqvist B (2000). Mechanisms behind positive diversity effects on ecosystem functioning : testing the facilitation and interference hypothesis. Oecologia 134: 554-559.

Kaspari M, Yanoviak SP (2008). Biogeography of litter depth in tropical forests : evaluating the phosphorus growth rate hypothesis. Funct. Ecol., 22: 919-923.

Kautz G, Topp W (2000). Acquisition of microbial communities and enhanced availability of soil nutrients by the isopod Porcellioscaber (Latr.) (Isopoda: Oniscidea). Biol. Fert. Soils, 31: 102-107.

Kurzatkowski D, Martins C, Hofer H, Garcia M, Forster B, Beck I, Vlek P (2004). Litter decomposition, microbial biomass and activity of soil organic matter in three agroforestry sites in central Amazonia. Nutr. Cyclingin Agroecosyst., 69: 257-267.

Lavelle P, Spain AV (2002). Soil Ecology. Kluwer. Academic Publishers, Dordrecht, The Netherlands.

Lavelle P (1988). Earthworms activities and the soil system. Biol. Fert. Soils, 6: 237-251.

Lavelle P, Blanchard E, Martin A, Martin S, Spain A, Toutain F, Barois I, Schaefer R (1993). A hierarchical model for décomposition in terrestrial ecosystems – application to soils of the humid tropics. Biotropica 25: 130-150.

Lecerf A, Dobson M, Dang CK, Chauvet E (2005). Riparian plant species alters trophic dynamics in detritus-based stream ecosystems. Oecologia 146: 432-442.

Leon JD, Osorio NW (2014). Role of Litter Turnover in Soil Quality in Tropical Degraded Lands of Colombia. The Scientific World Journal. Pp. 1-11.

Letouzey R (1968). Etude phytogeographique du Cameroun. Ed Le chevalier, Paris, p. 511.

Li LJ, Zeng DH, Yu ZY, Pan ZP, Yang D, Liu YX (2011). Impact of litter quality and soil nutrient availability on leaf decomposition rate in a semi-arid grassland of Northeast Chine. J. Arid Environ., 75 (9): 787-792.

Lussenhop J (1992). Mechanisms of micro-arthrop - microbial interactions in soil. Adv. Ecol. Res., 23: 1-33.

Madge DS (1965). Leaf litterfall and litter disappearance in tropical forest. Pedobiologia, 5: 273-288.

Maisto G, de Marco A, Meola A., Sessa L, de Santo AV (2011). Nutrient dynamics in litter mixtures of four Mediterranean maquis species decomposing in situ. Soil Biol. Biochem., 43 (3): 520-530.

Maraun M, Scheu S (1996). Changes in microbial biomass, respiration and nutrient status of beech (Fagussylvatica) leaf litter processed by millipedes (Glomerismarginata). Oecologia, 107: 131-140.

Marigo, G (1973). Sur une méthode de fractionnement et d'estimation des composées phénoliques chez les végétaux. Analusis, 2: 10-110.

Marinissen JCY, Bok J (1988). Earthworm-amended soil structure: its influence on Collembola population population in grassland. Pedobiologia, 32: 243-252.

McClaugherty CA, Pastor J, Aber JD, Melillo JM (1985). Forest litter decomposition in relation to soil nitrogen dynamics and litter quality. Ecology, 66 (1): 266-275.

McKie BG, Woodward G, Hladyz S, Nistorescu M, Preda E, Popescu C, Giller PS, Malmqvist B (2008). Ecosystem functioning in stream assemblages from different regions: contrasting responses to variation in detritivore richness, evenness and density. J. Animal Ecol., 77: 495-504.

Meyer WM III, Ostertag R, Cowie RH (2013). Influence of Terrestrial Molluscs on Litter Decomposition and Nutrient Release in a Hawaiian Rain Forest. Biotropica, 45(6): 719–727.

Mulder CPH, Koricheva J, Huss-Danell K, Hogberg P, Joshi J (1999). Insects affect relationships between plant species richness and ecosystem processes. Ecol. L., 2: 237-246.

Parsons SA, Congdon RA, Lawler IR (2014). Determinants of the pathways of litter chemical decomposition in a tropical region. New Phytol., 203: 873–882.

Paynes WA, Went CW, Hossner LR, Gates CE (1997). Estimating Pearl Millet leaf area and specific leaf area. Agron. J., 83: 937-941.

Poinsot-Balaguer N, Racon L, Sadaka N, Lepetit J (1993). Effects of tannin compounds on two species of Collembola. Eur. J. Soil Biol., 29: 13-16.

Rawlins AJ, Bull ID, Poirier N, InessonP, Evershed RP (2006). The biochemical transformation of oak (Quercus robur) leaf litter consumed by the pill millipede (Glomeris marginata). Soil Biol. Biochem. 38: 1063-1076.

Reiss J, Bridle JR, Montoya JM, Woodward G (2009). Emerging horizons in biodiversity and ecosystem functioning research. Trend. Ecol. Evol., 24(9): 505-514.

Roscher C, Thein S, Schmid B, Scherer-Lorenzen M (2008). Complementarity nitrogen use among potentially dominant species in a biodiversity experiment varies between two years. J. Ecol., 96: 477-488.

Rotheray TD, Boddy L, Jones TH (2009). Collembola foraging responses to interacting fungi. Ecol. Entomol., 34: 125-132.

Sokal JR, Rohlf RR (1981). Biometry. Ed Freeman, H. W. and Co, Sans Francisco, p 520.

Suberkropp K (1992). Interactions with invertebrates. The Ecology of Aquatic Hyphomycetes, Ed Bärlocher F, p. 118-133.

Suseela V, Tharayil N, Xing B, Dukes JS (2013). Labile compounds in plant litter reduce the sensitivity of decomposition to warming and altered precipitation. New Phytol., 200: 122–133.

Swift MJ, Anderson JM (1989). Decomposition. In Tropical rain forest ecosystems: ecosystems of the world, Ed Leith H, Werger MJA, Elsevier, Amsterdam, Pp. 547-569.

Swift MJ, Heal OW, Anderson JM (1979). Decomposition in terrestrial ecosystems. University of California Press, Berkeley.

Taylor BR, Parkinson D (1988). Patterns of water absorption and leaching in Pine and Aspen leaf litter. Soil Biol. Biochem. 20: 257-258.

Tiunov AV, Scheu S (2005). Arbuscularmycorrhizas and Collembola interact in affecting community composition of saprotrophic microfungi. Oecologia, 142: 636-642.

Trofymow JA, Moore TR, Titus B, Prescott C, Morrison I, Siltanen M, Smith S, Fyles J, Wein R, Camire C, Duschene L, Kozak L, Kranabetter M, Visser S (2002). Rates of litter decomposition over 6 years in Canadian forest: influence of litter quality and climate. Can. J. Forest Res., 3: 789-804.

Updegraff DM (1969). Semi-micro determinate of cellulose in biological material. Anal. Biochem., 32: 420-424.

van Dam O (2001). Forest filled with gaps : effects of gap size on water and nutrient cycling in Tropical Rainforest. A study in Guyana. Tropenbos-Guyana Series 10, Tropenbos-Guyana programme, Georgetown, Guyana.

van Ruijven J, Berendse F (2003). Positive effects of plant species diversity on productivity in the absence of legumes. Ecol. L., 6: 170-175.

van Soest PJ (1965). Use of detergent in analysis of fibrous feeds. III Study of effects of heating and drying on yield of fiber and lignin in forages. J. Assoc. Office. Anal. Chem., 48: 785-790.

Wall DH, Bradford MA, St John MG, Trofymow JA, Behan-Pelletier V, Bignell DE (2001). Global decomposition experiment shows soil animal impacts on decomposition are climate-dependent. Glob. Change Biol., 14: 2661-2677.

Wardle DA (2002). Communities and ecosystems : linking the above ground and below ground components. Princeton University Press,

Princeton.

Yonkeu S (1993).Végétation des pâturages de l'Adamaoua (Cameroun). Ecologie et potentialité pastorales. Thèse de Doctorat, Université de Rennes, France, PP. 207.

Zimmer M, Kautz G, Topp W (2005). Do woodlice and earthworms interact synergistically in leaf litter decomposition? Funct. Ecol., 19: 7-16.